Madroño, Vol. 55, No. 3, pp. 216–222, 2008

THE ROLES OF FLOODS AND BULLDOZERS IN THE BREAK-UP AND DISPERSAL OF *ARUNDO DONAX* (GIANT REED)

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Abstract

Arundo donax L. (Poaceae) is an invasive grass that severely degrades riparian habitats. It grows in many-stemmed clumps and, in California, spreads vegetatively only. Currently, *A donax* is thought to invade new areas through fragments broken from established clumps during flood events. But the role of flooding in generating fragments is based on anecdotal evidence only and has not been adequately studied. I examined *A. donax* clump break-up and reproduction via fragmentation in the Tijuana River Valley, California. I found that: (1) the majority of the new recruits from fragments grew from rhizome fragments (85% of 54) rather than stem fragments; (2) during the record rainfall of 2004–2005, flood waters damaged the rootstock of only a small proportion of clumps in the flood zone (7%; n = 46 clumps), and relatively few recruits from fragments subsequently became established in the valley at large (0.048 recruits 100 m^{-2}); and (3) during emergency channel maintenance along one tributary, bulldozers severely damaged the rootstock of all clumps growing on the channel bank (n = 3 clumps), and many recruits from fragments subsequently became established downstream of the bulldozer activity (2.92 recruits 100 m^{-2}; 61 times the number in the valley at large). These results indicate that, in the Tijuana River Valley, flood events only rarely break up *A. donax* rootstock and wash rhizomes downstream, and bulldozers play an important, and overlooked, role in the break-up and dispersal of *A. donax*. To reduce the spread of *A. donax* via rhizome fragments, regulatory agencies should require appropriate management practices when bulldozers are used in the presence of *A. donax*, and land managers should not use bulldozers when attempting to eradicate *A. donax*.

Key Words: *Arundo donax*, dispersal, flooding, giant reed, invasive species, non-indigenous species, plant fragments, rhizomes.

Arundo donax L. (Poaceae), giant reed, is a large, invasive grass from Eurasia that severely degrades riparian habitats in many temperate areas of the world (Dudley 2000; Global Invasive Species Database 2005). In California, a tremendous amount of effort has gone into controlling its spread (Katagi et al. 2002), but it is still common in most watersheds and even the dominant plant along many reaches (Neill and Giessow 2004). To determine the best strategy for control of any invasive plant, one needs detailed knowledge of its means of spread (Radosevich et al. 1997). *Arundo donax* spreads vegetatively in California, as no seedlings or viable seeds have been found (Perdue 1958; Else 1996; Johnson et al. 2006). The vegetative expansion of established clumps via lateral growth of rhizomes (Decruyenaere and Holt 2005; Boland 2006) and via layering of stems (Boland 2006) has received some recent attention, but there is little information on the formation of new clumps from vegetative fragments (cf. Else 1996; Boland 2006).

The conventional wisdom regarding the spread of *A. donax* via fragmentation is simple: during flood events, fragments are broken from established clumps and dispersed downstream where they subsequently sprout and grow into new clumps. Bell (1993), for example, states that "*(f)lood events break up clumps of Arundo and spread the pieces downstream. Fragmented stem nodes and rhizomes can take root and establish as new plant clones*." This idea has been repeated many times and has become entrenched in the *A. donax* literature (e.g., Else 1996; Bell 1997; DiTomaso 1998; Kelly 1999; McWilliams 2004). But the central premise – that flood events cause the break-up of clumps – is based on anecdotal evidence only and has not been adequately examined.

No other method of fragmentation has yet been proposed. But there are anthropogenic forces at work in watersheds that can influence *A. donax* break-up and dispersal. In the California wildlands where *A. donax* has become abundant, heavy equipment, such as bulldozers, loaders, excavators and tractors, are frequently used to maintain river channels, to construct flood-control berms beside agricultural fields, to maintain dirt roads, to dig quarries, and even to control *A. donax* (personal observations). I have observed bulldozers and other heavy equipment undercut, break up and move clumps of *A. donax*, and I suggest that they play an important, and heretofore overlooked, role in the break-up and dispersal of *A. donax*.

The purpose of this study was to examine vegetative reproduction via fragmentation in *A. donax*. First, I asked the question: What plant parts (stems or rhizomes) most commonly become successful recruits? Then I conducted observations and surveys that focused on the roles of flood flows and bulldozers in the break-up of established clumps, the dispersal of fragments and the recruitment of new clumps. The results of this study provide a new view of the mechanism of break-up and dispersal of *A. donax* that elevates the role of mechanical disturbance and suggests that new management practices are urgently needed if *A. donax* is to be successfully controlled.

Study Site

The study was conducted in the Tijuana River Valley, California, which is a coastal floodplain at the end of a large (448,000 ha) watershed that is partly in Mexico. The valley spans 1457 ha at approximately sea-level and includes a county regional park, a state park, and a national wildlife refuge (Concur 2000; Boland 2006). The valley contains prime riparian and salt marsh habitats that have been invaded by invasive, non-native species, including *A. donax*, salt cedar (*Tamarix* spp.), and castor bean (*Ricinus communis*). *Arundo donax* is common in the valley (Southwest Wetlands Interpretive Association 2002) and in much of the rest of the watershed upstream (Woch 2005).

This study was conducted between 2004 and 2006. The 2004–2005 rainfall year was the third wettest in San Diego history (57.2 cm of precipitation; Western Regional Climate Center 2006), and the unusually heavy rainfall produced many days of high flows in the Tijuana River Valley—172 days when the average daily flow rates were >1 m^3 sec^{-1} (Boland 2006; International Boundary & Water Commission 2006). During January 2005, emergency channel maintenance was conducted in Smuggler's Gulch, a narrow, sandy tributary leading to the main river flood plain. High flows threatened to breach the channel banks and flood neighboring farms, so bulldozers were used along an 800 m section to deepen the channel by working the bottom sediment into the flowing stream and to raise the banks by depositing sediment from the channel onto the banks. No other major bulldozing occurred in the flood zone in the valley between 2003 and 2006.

Methods

Plant Fragments that Become Successful Recruits

To determine which *A. donax* plant parts most often become successful recruits, extensive searches for new recruits from plant fragments were conducted throughout the valley during the spring and summer of 2005. These searches included: (a) valley-wide belt transects that covered 0.84 ha – described in more detail below and in Boland (2006); (b) localized surveys that covered 0.12 ha – also described below; and (c) additional searches that covered approximately 0.3 ha in selected areas where new recruits from fragments were expected to occur, e.g., areas containing debris piles. The total area surveyed was therefore >1.25 ha. When a sprouting fragment was found, the sprout was dug up and the fragment was identified as either a piece of rhizome or stem (i.e., culm).

The Role of Flood Flows

Observations of A. donax *Clumps During Flooding Events.* To determine whether flood flows broke up clumps of *A. donax*, I watched the behavior of *A. donax* clumps in the flood waters throughout the severe winter of 2004–2005. During more than 30 visits to the valley, I observed clumps from bridges while flooding was occurring. I looked for evidence of damage to clumps due to flood flows, e.g., breaking of rhizomes, undermining of rootstock, and washing-away of whole clumps during the flooding.

Estimation of Flood Damage to A. donax *Rootstock.* To assess the damage to clumps of *A. donax* caused by the exceptional winter of flood events, I examined clumps before and after the 2004–2005 floods. I had photographed 63 *A. donax* clumps in all parts of the valley, during summer 2004, as part of a separate study. During summer 2005, I reexamined these clumps. At each clump, I compared the clump with the photo taken before the flooding and estimated the amount of flood damage to the rootstock as either none, slight (area of <1 m^2 missing), moderate (1–3 m^2 missing) or severe (>3 m^2 missing). During the visit, the clump was also determined to be inside or outside the 2004–2005 flood zone according to its position relative to flood debris. The clumps were located throughout the valley, both inside (46 clumps) and outside (17 clumps) the flood zone. Clumps outside the flood zone were not expected to be damaged by flood flows but their results are presented for comparative purposes.

Abundance of Sprouting A. donax *Fragments in the Valley After the Flooding.* To determine the number of new recruits from fragments after the 2004–2005 flooding, I surveyed the valley during June 2005 using the same procedures as Else (1996). Eight transects across the river valley were chosen in a stratified-random manner (Boland 2006). The transects were 2 m-wide belts that ran perpendicular to the river channel and extended from the southern edge to the northern edge of the 2005 flood zone. The boundary of the flood zone was determined by the presence of debris indicating the highest flood level of the 2004–

2005 flood season. Transect lengths varied depending on the width of the flood zone (range = 97–865 m; n = 8). The total area surveyed was 0.84 ha. Within each transect, the number of new *A. donax* recruits from fragments was counted. Each new recruit was excavated and determined to be from a fragment if it was not attached to a parent plant (as opposed to a new recruit formed via stem layering, which would have a visible connection to the parent plant; Boland 2006). Recruits from fragments were further classified as being from a fragmented stem or rhizome. The average density of new recruits from fragments in the valley as a whole, i.e., resulting from flood events only, was estimated from this survey and reported as the number per 100 m^2.

The Role of Bulldozers

Observations of A. donax *Clumps During Bulldozer Activity.* The January 2005 emergency channel maintenance at Smuggler's Gulch provided an opportunity to observe the effects of bulldozers on *A. donax*. I watched for cutting of rhizomes, undermining of rootstock, pushing of live material into the channel flow, and depositing of excavated *A. donax* onto channel banks.

Estimation of Bulldozer Damage to A. donax *Rootstock.* To assess the damage caused by bulldozers to rootstocks of *A. donax*, I examined the three large clumps growing on the banks of Smuggler's Gulch in January 2005, immediately after the maintenance was completed. I did a follow-up survey in June 2005 to further evaluate damages due to the maintenance activity. For each clump, I estimated the amount of bulldozer damage to the rootstock as either none, slight (area of <1 m^2 missing), moderate (1–3 m^2 missing) or severe (>3 m^2 missing) based on photos and previous knowledge of clump size from prior site visits.

Abundance of Sprouting A. donax *Fragments Downstream of a Bulldozed Channel.* Immediately after the dredging at Smuggler's Gulch in January 2005, I saw vegetation debris scattered over a cleared staging area located in the floodplain approximately 150 m downstream of Smuggler's Gulch. To determine the number of new recruits from fragments occurring downstream of the bulldozer activity, I surveyed this staging area for sprouting fragments in June 2005. I divided the staging area into two survey sites, each 100 m × 50 m and, within each site, searched for new *A. donax* recruits in six randomly-chosen, 2 m × 50 m belt transects (*sensu* Else 1996; Boland 2006). The total area surveyed was 0.12 ha. Within each transect, the number of new recruits from fragments was counted. Each new recruit was excavated and identified as a fragment of either stem or rhizome. The average density of new recruits below Smuggler's Gulch, i.e., due to bulldozer activity, was estimated from this survey, reported as the number per 100 m^2, and compared to the density of new recruits from fragments in the river valley as a whole using the Chi-square Test with Yates' correction.

Results

Plant Fragments that Become Successful Recruits

In extensive searches of the Tijuana River Valley, covering >1.25 ha, I found a total of 61 new *A. donax* recruits sprouting from vegetative fragments. For 54 of these, the fragment type could be unmistakably identified as rhizome or stem, but seven were too deeply buried to be identified. Of the 54 identifiable recruits, 46 (85%) were from rhizome fragments, and 8 (15%) were from stem fragments. These results indicate that, while fragments of both rhizomes and stems do sprout, rhizome fragments are the more likely to successfully sprout and give rise to new clumps. Therefore, in examining the roles of floods and bulldozers on the break-up of *A. donax* clumps, I have focused on the fragmentation of rhizomes and not of stems.

The Role of Flood Flows

Observations of A. donax *Clumps During Flooding Events.* During the severe floods of 2004–2005, there was no evidence of *A. donax* clumps being broken-up or otherwise damaged by flood waters. During low flows, water flowed around the clumps without disturbing the stems or rootstock. During high flows, water flowed through and over the clumps, dead stems were swept away, and live stems swayed violently in the currents but remained attached to the rootstock. All rootstocks appeared to remain intact.

Estimation of Flood Damage to A. donax *Rootstock.* Examination of *A. donax* clumps after the floods of 2004–2005, revealed that clumps suffered relatively little damage to their rootstock due to flooding. Of the 46 clumps growing inside the flood zone, 43 (93%) showed no signs of damage to the rootstock (Table 1). Only three clumps (7%) had damaged rootstocks where flood flows had partially undermined and swept away a portion of their rootstocks. In each case, the extent of damage was slight to moderate, with less than 3 m^2 of the rootstock lost. As expected, the 17 clumps growing outside the flood zone showed no sign of damage to their rootstocks (Table 1).

Abundance of Sprouting A. donax *Fragments in the Valley After the Flooding.* Extensive surveys

TABLE 1. THE DEGREE OF DAMAGE TO *ARUNDO DONAX* CLUMPS PHOTOGRAPHED IN SUMMER 2004 AND REEXAMINED IN SUMMER 2005. Damage is described as slight (rootstock area of <1 m^2 missing), moderate (1–3 m^2 missing) or severe (>3 m^2 missing). TJRV = Tijuana River Valley.

Site	Clumps (n)	Source of Damage	Degree of damage to rootstocks				% Damaged
			None	Slight	Moderate	Severe	
TJRV—Inside Flood Zone	46	flooding	43	2	1	0	7%
TJRV—Outside Flood Zone	17	none	17	0	0	0	0%
Smuggler's Gulch Bank	3	bulldozers and flooding	0	0	1	2	100%

after the floods of 2004–2005 showed that new *A. donax* recruits growing from fragments were rare in the Tijuana River Valley. Only four recruits from fragments were encountered in the valley-wide surveys, i.e., 0.048 recruits per 100 m^2 (Table 2).

The Role of Bulldozers

Observations of A. donax *Clumps During Bulldozer Activity.* During the January 2005 channel maintenance in Smuggler's Gulch, bulldozers undermined *A. donax* clumps and easily cut their rootstocks. Front-loaders piled the dredge spoils on the banks nearby, and this spoil contained live *A. donax* pieces, which later developed into 15 new clumps, a five-fold increase in clumps on the bank. In addition, the bulldozers pushed living *A. donax* material into the channel where it was washed downstream.

Estimation of Bulldozer Damage to A. donax *Rootstock.* Examination of the *A. donax* clumps on the banks of Smuggler's Gulch after the channel maintenance activities confirmed that bulldozers had substantially reduced the rootstocks of all three large clumps and caused moderate to severe damage to each (Table 1).

Abundance of Sprouting A. donax *Fragments Downstream of a Bulldozed Channel.* New recruits growing from fragments were abundant in the flood zone immediately downstream from the bulldozer work in Smuggler's Gulch. A total of 35 recruits were present in the surveys, at a density of 2.92 per 100 m^2 (Table 2). This density was 61-times the density of new recruits in the entire valley. Therefore, the density of recruits downstream of the bulldozer activity was significantly greater than the density of recruits in areas not influenced by the bulldozers (Chi-square Test with Yates' correction; $P < .005$).

DISCUSSION

The Importance of Rhizome Fragments in the Dispersal of *A. donax*

To understand dispersal in *A. donax*, one needs to know which plant part is responsible for most of the new recruits. In the Tijuana River Valley, the majority of the new fragment recruits (85%) were growing from rhizome fragments, and many fewer were growing from stem and branch fragments. This result is not surprising, as *A. donax* rhizomes have been the most viable fragment under both lab (Decruyenaere and Holt 2001) and field conditions (Else 1996), and farmers use rhizomes when propagating *A. donax* (Hoshovsky 2003). *Arundo donax* rhizomes are thick and solid, and designed for carbohydrate storage rather than for rapid expansion of the clump (Boland 2006). They provide the plant with a site for resource storage protected from fire, frost, grazers and desiccation. When dispersed, they provide abundant resources for the successful establishment of a new clump. As for the other plant parts, main stems and branches are hollow and, although their fragments can sprout (Motamed and Wijte 1998), they are less likely to become successful recruits (Dudley 2000; this study). What these results show is that when studying the reproduction of *A. donax* by vegetative fragmentation one needs to focus primarily on rhizomes and the mechanisms that break live rhizomes from rootstocks.

TABLE 2. THE NUMBER AND DENSITY OF NEW *ARUNDO DONAX* RECRUITS FROM FRAGMENTS IN THE ENTIRE TIJUANA RIVER VALLEY AND IN THE FLOODPLAIN IMMEDIATELY DOWNSTREAM OF THE BULLDOZED CHANNEL, SMUGGLER'S GULCH.

	Entire Tijuana River Valley	Downstream of Smuggler's Gulch
Bulldozer-use upstream?	no	yes
Surveyed area (ha)	0.837	0.12
Total no. of recruits from fragments	4	35
Density of recruits from fragments (100 m^{-2})	0.048	2.92
Test of densities (chi-square)	$P < .005$	

The Role of Flood Flows

Currently it is thought that flooding is the mechanism responsible for the break-up of *A. donax* (e.g., Bell 1993; McWilliams 2004). However, when *A. donax* clumps were observed during an extremely wet year—when extensive fragmentation would be expected—fragmentation and the production of new recruits were found to be rare. I found that only a small proportion of the clumps were undermined (7%), only a few rhizomes were removed by flooding (<3 m^2 at each clump) and relatively few recruits from fragments became established in the valley (0.048 recruits 100 m^{-2}). Furthermore, in years when flows are average or below average, one sees even fewer instances of fragmentation and fewer recruits (personal observations). Floods do not easily break off rhizomes because rootstocks and the soils they bind create effective barriers to water flows, and because rhizomes are not easily broken (personal observations). Hence, although the conventional wisdom gives the impression that *A. donax* clumps are frequently and easily fragmented by flood flows (Bell 1993), this is not the case.

The Role of Bulldozers

In contrast to flood events, bulldozers and other earthmoving equipment easily cut, undermined, and moved large sections of *A. donax* rootstocks in the Tijuana River Valley. By doing so bulldozers influenced both the local and long-distance dispersal of *A. donax*. At Smugglers Gulch, bulldozers increased the number of clumps on the bank five-fold and increased the density of recruits downstream by 61-times. These results show that bulldozers can play a major role in the break-up, dispersal and propagation of *A. donax*.

Bulldozers are a "disturbance" in the traditional sense (e.g., Begon et al. 1996), in that they create gaps into which *A. donax* can invade. They also act as vectors that carry rhizomes relatively short distances, and act as dispersal facilitators that produce the propagules (rhizomes) and leave them to be dispersed over long distances via river flows. It is not unusual for mechanical equipment to facilitate the dispersal of invasive plants (e.g., USDA Forest Service 2001). Usually the equipment is the vector, carrying the plant from an infected area to an uninfected area. But, mechanical equipment can also be the agent that produces the dispersed material. When mowers are used to control any of several invasive waterweeds, e.g., leafy elodea (*Egeria densa*), parrot's feather (*Myriophyllum aquaticum*), Eurasian water-milfoil (*Myriophyllum spicatum*), they cut and release plant fragments that can drift into, and establish in, new habitats (Bossard 2000; Godfrey 2000; Hoshovsky and Anderson 2000). Bulldozers and waterweed mowers therefore play similar roles in the spread of their respective invasive plants.

There have been some recent questions about the spread of *A. donax* in California. For instance, Johnson et al. (2006) state: "*The invasion of California riparian areas by Arundo continues despite efforts to control its spread, and there remains some uncertainty as to how it is able to do so*." They determined that seed production was not the mechanism by which *A. donax* was invading. I suggest that the "continued invasions" of *A. donax* they describe are due to bulldozer activities in the watersheds. The findings in the Tijuana River Valley show that much of the recruitment of new *A. donax* clumps can be separated, in both space and time, from the bulldozer event that produced them. The dislodged rhizomes can be dispersed hundreds of meters, and the time between the bulldozer impact and the obvious growth of the new recruits can be up to ten months. Someone finding new recruits in a flood zone may not realize that the recruits came from a bulldozer disturbance many months earlier, and possibly many hundreds of meters upstream. This separation of cause and effect has probably contributed to our slow appreciation of the role that bulldozers play in the spread of *A. donax*.

Consequences for Management

Bulldozers are used in *A. donax* areas to dredge channels, to raise channel banks, to cut dirt roads, to mine for sand and gravel, to cut and clear vegetation, etc. Now, with evidence that bulldozers promote the dispersal of *A. donax*, permitting agencies should insist on appropriate management practices for these kinds of activities. The practices on-site could include spraying of *A. donax* clumps with herbicide before, during, and after earthmoving activities, and the installation and maintenance of plant-debris catchers during the project. In addition, all soil and plant debris that is removed from the site should be treated appropriately to prevent the spread of *A. donax*.

Another problem is that bulldozers are sometimes used to eradicate *A. donax* (Bell 1997; Oakins 2001). Mechanical excavation would be an acceptable option if the method were 100% efficient in removing *A. donax* rhizomes, but the method is not that efficient. Typically, at these *A. donax*-control sites, bulldozers excavate the rootstock and front-loaders load the material into a tub-grinder on-site. The finely-ground material produced by the tub-grinder is not able to sprout (Boland unpublished data). But *A. donax* rootstocks are incompletely removed from the soil, rhizome pieces are dropped along the way to the tub-grinder, and other pieces are thrown out uncut by the tub-grinder (personal observations) and these rhizome pieces are capable of sprouting (Boland unpublished data). At one treatment site on the Santa Margarita River where some mechanical excavation and tub-grinding was conducted, Giessow and Giessow (1999) noted that "*most of the* Arundo *resprouts that occurred resulted from small pieces of rhizome that broke off during the mechanical removal process*." Therefore, even the well-intentioned use of heavy equipment as agents for *A. donax*-control can undermine an eradication effort by producing fragments that propagate *A. donax* on-site and downstream. Until safe methods are developed, mechanical equipment should be limited to dealing with only the above-ground biomass of *A. donax*, and rhizomes should be left in place and treated chemically.

It is time to recognize the threat posed by bulldozers and other earthmovers in the unintentional break-up and dispersal of *A. donax*, and to focus our efforts on preventing this method of spread.

Acknowledgments

Partial support for this research came from Southwest Wetlands Interpretive Association (SWIA) through a Proposition 13 grant from the California State Water Resources Control Board. I thank Carl Bell, Jeff Crooks, John Hunter, Chris Nordby, Bill Winans, Deborah Woodward and two anonymous reviewers for helpful comments on an early draft of this manuscript.

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